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# An overview of characteristics of municipal solid waste fuel in China: Physical, chemical composition and heating value

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ABSTRACT

In this paper, the characteristics of physical and chemical composition of municipal solid waste (MSW) in China were reviewed and the statistical indexes, namely mean value, standard deviation, coefficient of variation, and *t*-test, were applied to analyze the physical composition, proximate, ultimate analysis, and heating value. Listed in decreasing sequence, the physical components of Chinese MSW are in food residue, non-combustibles, plastics, paper, textiles, wood waste, and rubber. In food residue, the average elementary hydrogen (H), oxygen (O) and nitrogen (N) content varied greatly with samples and the chlorine (Cl) and moisture contents were extraordinarily high. While conversely, the components of wood waste were simple and different components displayed little disparity in characteristics. The elemental compositions of paper and textiles were also simple. The properties of chlorine-free plastics (polyethylene, polypropylene and polystyrene) were consistent, with high volatile matter, carbon (C) and H content. The mean higher heating value (HHV) of polrvinyl chloride (PVC) was about a half of that of chlorine-free plastics, because the Cl content of PVC was approximate 50%. It suggested that plastics with or without chlorine should be separated as possible. The HHV of different rubbers varied sharply, from 21,812 to 38,868 kJ/kg. A model was proposed to predict the proximate and ultimate analysis and heating value from physical composition, in which the PVC fraction in plastics and the supplementary moisture coefficient were introduced. The results showed that the predicted results fitted well with the measured ones.



**Contents**



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## 1. Introduction and scope

### 1.1. The generation and management of municipal solid waste in China

China, as a developing country, has the world's largest population of about 1.37 billion according to the population census in 2010. With the rapid development of national economy, the ever-accelerating urbanization and the continuous improvement of residents' living standard, the yield of solid waste, particularly municipal solid waste (MSW), are constantly increasing, reaching 170.81 million tons by 2012 [1]. Annual generation of MSW in China is expected to reach 172 and 200 million tons by 2013 and 2020, respectively. Therefore, proper waste treatment is hence an urgent and important task for the continued development of cities [2].

Incineration is preferred to landfill disposal in MSW treatment [3] due to its decomposition and immobilization of hazardous substances, high-degree volume reduction, low space requirement and effective energy recovery [4]. In China, waste incineration has developed very rapidly since 1980s. The incinerated MSW increased from 3.70 million tons in 2003 to 35.84 million tons in 2012 and the number of incineration plants increased from 47 to 138 [1,5]. In recent years, waste pyrolysis and gasification are also drawing great concern [6]. They represent an alternative process to enhance both the energy and economic value of MSW utilization, as well as to provide products that have potential to be further utilized [7].

### 1.2. Problems regarding MSW thermal conversion investigations in China

Due to the uniqueness of MSW from other fuels, existing research results attained from studies into other solid fuels (coal, peat, petroleum coke, and biomass) can hardly be applied directly in the field of MSW. In a certain number of investigations into MSW, incomplete scientific approaches or scattered and non-uniform data lead to inaccurate results. To obtain a comprehensive understanding of MSW, the characteristics of MSW and some problems in research into MSW are elucidated in this paper.

(1) The composition of MSW is complicated and is impacted by a number of factors. Not only does MSW composition vary across time and region, disparity among related data provided by different researchers can also be detected [8–18], as shown in Table 1. In 1997, the percentage of food residue in MSW of Qingdao was 42.20%, while that of Xi'an was 15.74%. Even with the same region, the MSW composition also varied across time. For example, food residue made up 85.8% of the waste of Dalian in 1993, while the percentage decreased to 59.86% by 2007; meanwhile, the content of paper, textiles and plastics increased accordingly.

(2) The percentage of moisture and ash contents of different types of MSW shows noteworthy difference, as shown in Table 1. The moisture in MSW of Shanghai in 1998 was 58.87%, while that of Beijing MSW in the same year was 39.31% [21]. Moisture and ash contents influence the heating value (HV) of MSW to a considerable extent. LHV of Dongguan MSW was as high as 8847 kJ/kg, while that of MSW in Wuhu in 1997 was only 2863 kJ/kg: the latter was less than 1/3 of the former. The volatile matter of different MSW varies, as shown in Table 1. The volatile matter of Hong Kong waste as dry base in 1997 was 35.31%, while that of Xi'an in the same year was only 20.03%. The volatile matter impacts the ignition of MSW incineration. The higher volatile matter content, the more easily MSW can be ignited. In pyrolysis and gasification, the volatile matter influences composition and yield of the gas products. Higher the volatile matter content, the more gas pyrolysis and gasification generate. However, previous investigations are normally based on a particular type of waste. Considering the complicatedness of various influential factors that contribute to the disparity of content of MSW, and it is difficult to gain more extensive and representative conclusions.

(3) Due to the complexity of MSW, previous research concentrated on the thermochemical properties of certain types of substance in MSW [42–51]. Nevertheless, for a specific component in MSW, such as plastics, different researchers reported diverse proximate and ultimate analysis results and thermal kinetic parameters [42,43,48,52]. In fact, plastics are not a single component, since it comprises different materials such as polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC). Materials have various proximate and ultimate analysis results, as well as thermal kinetic parameters. For instance, the C content of PE is as high as 85.5% [53], while that of PVC was only 34.24% and the Cl content of PVC is 52.21%. Different elemental compositions will lead to different gas products after thermochemical processes. Furthermore, the combustion of materials containing chlorine may produce persistent organic pollutions (POPs) such as polychlorinated dibenzo-*p*-dioxin, polychlorinated dibenzofurans (PCDD/Fs), and polychlorinated biphenyls (PCBs) [54] which are highly toxic and may have carcinogenic and mutagenic effects [55]. However, some ultimate analysis did not detect the Cl content, and even mistook the Cl content for O content, which led to serious errors [45].

(4) The variation of heating value of MSW will greatly impact the stable operation of incinerator. According to engineering experience, to ensure complete combustion, the monthly average LHV of MSW should be more than 4127 kJ/kg [56]. However, HV is seldom reported in detail. Analytical method is important when determining the accuracy and validity of the data. The HV are usually described in terms of HHV, LHV, or bomb heating value (BHV). Although these terms are related,

**Table 1**
The physical and chemical characterizations of MSW in typical cities of China.

| City | Year | Physical composition (wt%) | | | | | | | Proximate analysis (wt%) | | | | Ultimate analysis (wt%) | | | | | | $Q_{net,w}$ (kJ/kg) | $Q_{gr,d}$ (kJ/kg) | Reference used |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Food residue | Wood waste | Paper | Textiles | Plastics | Rubber | Non-combustibles | $M_w$ | $A_d$ | $V_d$ | $FC_d$ | $C_{daf}$ | $H_{daf}$ | $O_{daf}$ | $N_{daf}$ | $S_{daf}$ | $Cl_{daf}$ | | | |
| Beijing | 1990 | 24.89 | 4.13 | 4.56 | 1.82 | 5.08 | | 59.52 | | | | | | | | | | | | | [19] |
| | 1995 | 35.96 | 8.37 | 16.18 | 3.56 | 10.35 | | 25.58 | | | | | | | | | | | | | [19] |
| | 1995 | 25.17 | 7.15 | 3.26 | 1.94 | 4.88 | | 57.58 | | | | | | | | | | | | | [20] |
| | 1996 | 56.00 | 8.60 | 11.80 | 2.80 | 12.60 | | 8.29 | | | | | | | | | | | | | [14] |
| | 1998 | 35.40 | 2.90 | 19.20 | 5.30 | 15.80 | | 19.39 | 39.31 | 34.65 | 57.09 | 8.27 | 58.51 | 8.27 | 31.81 | 1.17 | 0.23 | | 8242 | 16,343 | [21] |
| | 1998 | 36.74 | 9.12 | 17.89 | 4.11 | 11.35 | | 20.79 | | | | | | | | | | | | | [22] |
| | 2000 | 44.15 | 7.47 | 14.28 | 9.58 | 13.61 | | 10.91 | | | | | | | | | | | | | [23] |
| | 2000 | 44.37 | 7.51 | 14.35 | 2.03 | 13.68 | | 18.06 | | | | | | | | | | | | | [17] |
| | 2003 | 48.00 | 8.04 | 18.28 | 1.83 | 10.29 | | 13.56 | | | | | | | | | | | | | [23] |
| | 2003 | 56.28 | 4.03 | 6.68 | 1.86 | 10.30 | | 20.85 | | | | | | | | | | | | | [17] |
| | 2004 | 59.51 | 5.70 | 14.55 | 5.62 | 11.26 | | 3.36 | | | | | | | | | | | | | [22] |
| | 2004 | 54.60 | 3.04 | 7.56 | 1.83 | 11.27 | | 21.69 | | | | | | | | | | | | | [17] |
| | 2005 | 63.79 | 1.26 | 9.75 | 1.69 | 11.76 | | 11.75 | | | | | | | | | | | | | [24] |
| | 2005 | 54.55 | 3.04 | 7.55 | 1.83 | 11.26 | | 21.67 | 56.19 | | | | | | | | | | 3710 | | [25] |
| | 2006 | 63.40 | 1.80 | 11.10 | 2.50 | 12.70 | | 8.50 | 61.00 | | | | 58.26 | 7.80 | 32.12 | 1.56 | 0.26 | | 4560 | | [26] |
| | 2006 | 64.82 | 1.56 | 14.89 | 1.90 | 14.14 | | 2.69 | | | | | | | | | | | | | [22] |
| | 2008 | 66.19 | 3.28 | 10.89 | 1.19 | 13.11 | | 5.34 | | | | | | | | | | | | | [27] |
| | 2008 | 50.67 | 1.62 | 15.70 | 3.34 | 19.56 | | 9.11 | | | | | | | | | | | 3895 | | [18] |
| | 2009 | 63.21 | 3.21 | 12.57 | 1.21 | 15.30 | | 4.50 | | | | | | | | | | | 5322 | | [18] |
| | 2010 | 64.93 | 1.48 | 12.94 | 3.11 | 15.07 | | 2.47 | | | | | | | | | | | | | [22] |
| Changchun | 2000 | 75.73 | | 6.11 | 1.34 | 2.15 | | 11.27 | 51.00 | | | | 54.69 | 8.57 | 33.88 | 1.63 | 1.22 | | | | [29] |
| Changzhou | 1997 | 44.40 | 1.80 | 3.56 | 3.15 | 7.95 | | 39.14 | 43.04 | 65.01 | 30.02 | 4.97 | 55.80 | 8.09 | 34.04 | 1.69 | 0.39 | | 3007 | 7733 | [8] |
| Chengdu | 1996 | 71.50 | | 3.30 | 1.30 | 6.90 | | 17.00 | | | | | | | | | | | | | [14] |
| Chongqing | 1998 | | | | | | | | | | | | 54.26 | 7.55 | 36.05 | 1.82 | 0.33 | | 3155 | | [21] |
| | 2002 | 59.20 | 4.20 | 10.10 | 6.10 | 15.70 | 0.30 | 4.50 | | | | | | | | | | | | | [30] |
| Dalian | 1993 | 85.80 | 1.30 | 4.25 | 1.10 | 4.90 | | 2.47 | | | | | | | | | | | | | [14] |
| | 2007 | 59.86 | 2.10 | 14.39 | 4.67 | 16.19 | 1.43 | 1.36 | 61.74 | | | | | | | | | | 4491 | | [16] |
| Dongguan | 2002 | | | | | | | | | | | | 60.42 | 8.20 | 29.42 | 1.63 | 0.33 | | 8847 | | [21] |
| Fuyang | 2000 | 38.57 | 2.59 | 7.09 | 6.04 | 17.86 | 0.31 | 28.80 | | | | | 61.07 | 8.68 | 28.51 | 1.45 | 0.29 | | 6901 | | [21] |
| Fuzhou | 1999 | 36.09 | 1.39 | 6.26 | 2.37 | 12.30 | 0.07 | 40.19 | | | | | | | | | | | | | [10] |
| | 2000 | 60.17 | | 13.72 | 4.20 | 10.66 | | 9.10 | 53.05 | 27.95 | 62.41 | 9.64 | 56.91 | 7.96 | 33.43 | 1.49 | 0.22 | | 6055 | 16,912 | [21] |
| | 2000 | 41.73 | 1.45 | 5.05 | 2.70 | 8.93 | 0.62 | 37.39 | | | | | | | | | | | | | [31] |
| Guangzhou | 1994 | 76.07 | | 2.83 | 3.99 | 9.60 | | 7.74 | | | | | | | | | | | | | [20] |
| | 1996 | 60.17 | 1.06 | 5.40 | 3.40 | 8.99 | | 20.98 | 53.50 | 46.82 | 45.96 | 7.23 | 56.51 | 7.96 | 33.47 | 1.74 | 0.32 | | 4326 | 13,023 | [8] |
| | 2008 | 48.46 | 7.08 | 8.96 | 7.70 | 12.59 | | 15.21 | | | | | 51.90 | 5.27 | 39.76 | 1.84 | 0.14 | 1.08 | | | [32] |
| | 2008 | 52.00 | | 9.00 | 13.00 | 21.30 | | 4.70 | | | | | | | | | | | | | [27] |
| | 2011 | 37.76 | 2.26 | 8.10 | 20.44 | 25.55 | | 5.89 | | | | | | | | | | | | | [33] |
| Guilin | 2008 | 61.31 | | 4.96 | 1.80 | 28.18 | | 3.75 | | | | | | | | | | | | | [27] |
| Haikou | 1996 | 42.30 | 3.50 | 6.77 | 1.60 | 13.30 | | 32.40 | | | | | | | | | | | | | [14] |
| Hangzhou | 1997 | 58.19 | 1.20 | 3.68 | 2.23 | 6.62 | 1.01 | 27.07 | 51.56 | 54.71 | 39.02 | 6.28 | 55.93 | 7.98 | 33.87 | 1.82 | 0.41 | | 3569 | 10,744 | [8,9] |
| | 2001 | 34.00 | 2.90 | 4.60 | 4.30 | 18.60 | | 35.60 | | | | | | | | | | | 6018 | | [34] |
| Harbin | 1994 | 48.50 | | 4.25 | 1.60 | 3.68 | | 41.90 | | | | | | | | | | | | | [14] |
| Hong Kong | 1997 | 25.50 | 5.00 | 25.70 | 4.20 | 17.10 | | 22.50 | 33.56 | 35.31 | 56.44 | 8.25 | 58.25 | 8.25 | 32.28 | 0.96 | 0.25 | | | | [8] |
| Longgang | 1998 | 44.70 | 1.87 | 7.68 | 1.69 | 23.86 | | 20.20 | 47.20 | 40.47 | 51.27 | 8.26 | 64.32 | 9.20 | 25.06 | 1.17 | 0.25 | | 6730 | 16,101 | [8] |
| Luoyang | 2000 | 26.92 | 0.83 | 3.40 | 0.61 | 2.90 | 0.02 | 65.06 | | | | | | | | | | | | | [13] |
| Macao | 1992 | | | | | | | | 39.19 | 20.56 | 70.51 | 8.93 | 56.10 | 7.64 | 34.40 | 1.53 | 0.33 | | 9436 | 18,399 | [9] |
| Nanjing | 2001 | | | | | | | | 43.70 | 37.50 | 57.64 | 4.87 | 55.29 | 6.96 | 35.07 | 1.39 | 0.27 | 1.01 | 4197 | 10,290 | [35] |
| | 2008 | 70.59 | 1.04 | 8.32 | 3.05 | 14.18 | | 2.82 | | | | | | | | | | | | | [27] |
| Ningbo | 1996 | 53.69 | 1.10 | 5.40 | 2.96 | 7.90 | | 28.95 | 49.09 | 54.94 | 38.95 | 6.11 | 55.60 | 7.97 | 34.38 | 1.70 | 0.35 | | 3942 | 10,871 | [8,9] |
| | 1998 | 55.71 | 3.82 | 7.85 | 4.36 | 12.27 | | 15.99 | 51.49 | 36.91 | 54.25 | 8.85 | 58.00 | 8.03 | 32.10 | 1.53 | 0.33 | | 5833 | 15,706 | [21] |
| | 1999 | 55.90 | 1.00 | 5.10 | 4.50 | 13.80 | | 19.30 | 51.91 | 42.87 | 49.50 | 7.63 | 59.52 | 8.40 | 30.13 | 1.65 | 0.29 | | 5437 | 14,978 | [21] |
| Panjin | 1999 | 64.50 | 1.30 | 4.10 | 1.50 | 5.80 | | 22.80 | | | | | 54.16 | 7.66 | 35.98 | 1.82 | 0.37 | | 3222 | | [21] |
| Pudong | 1993 | 77.30 | 1.40 | 7.10 | 2.40 | 5.80 | | 6.00 | | | | | | | | | | | | | [20] |

**Table 1** (*continued*)

| City | Year | Physical composition (wt%) | | | | | | | Proximate analysis (wt%) | | | | Ultimate analysis (wt%) | | | | | | $Q_{net,w}$ (kJ/kg) | $Q_{gr,d}$ (kJ/kg) | Reference used |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Food residue | Wood waste | Paper | Textiles | Plastics | Rubber | Non-combustibles | $M_w$ | $A_d$ | $V_d$ | $FC_d$ | $C_{daf}$ | $H_{daf}$ | $O_{daf}$ | $N_{daf}$ | $S_{daf}$ | $Cl_{daf}$ | | | |
| | 1996 | | | | | | | | 51.58 | 35.05 | 56.38 | 8.57 | 58.70 | 8.33 | 31.35 | 1.37 | 0.25 | | 6343 | 16,863 | [8,9] |
| Qingdao | 1997 | 42.20 | | 4.00 | 3.20 | 11.20 | | 39.40 | 42.36 | 62.96 | 32.22 | 4.82 | 58.38 | 8.61 | 31.09 | 1.59 | 0.33 | | 4204 | 9773 | [8,9] |
| Qinhuangdao | 2003 | 43.35 | 0.91 | 6.84 | 3.80 | 4.33 | 0.11 | 40.66 | | | | | | | | | | | | | [29] |
| Shanghai | 1990 | 82.72 | 1.56 | 4.01 | 1.18 | 3.98 | | 6.55 | | | | | | | | | | | | | [36] |
| | 1991 | 82.09 | 1.44 | 4.23 | 1.14 | 4.19 | | 6.88 | | | | | | | | | | | | | [36] |
| | 1992 | 79.14 | 1.33 | 6.24 | 1.65 | 5.78 | | 5.85 | | | | | | | | | | | | | [36] |
| | 1993 | 72.93 | 1.89 | 8.36 | 1.97 | 7.58 | | 7.32 | | | | | | | | | | | | | [36] |
| | 1994 | 73.32 | 1.37 | 7.49 | 2.13 | 9.24 | | 6.45 | | | | | | | | | | | | | [36] |
| | 1995 | 71.65 | 1.47 | 6.50 | 2.17 | 11.21 | | 7.01 | | | | | | | | | | | | | [36] |
| | 1996 | 70.30 | 1.96 | 6.68 | 2.26 | 11.84 | | 6.97 | | | | | | | | | | | | | [36] |
| | 1997 | 70.09 | 1.44 | 8.05 | 2.24 | 11.78 | | 6.41 | | | | | | | | | | | | | [36] |
| | 1998 | 67.33 | 1.27 | 8.77 | 1.90 | 13.48 | | 7.25 | 58.87 | 27.26 | 62.45 | 10.29 | 59.16 | 8.19 | 30.88 | 1.50 | 0.27 | | 5763 | 18,786 | [21] |
| | 1998 | 65.58 | 1.14 | 6.01 | 1.30 | 12.90 | | 10.99 | | | | | | | | | | | | | [10] |
| | 2000 | 67.50 | 1.43 | 8.02 | 2.81 | 13.93 | | 6.26 | | | | | | | | | | | | | [36] |
| | 2001 | 69.96 | 1.26 | 8.20 | 2.38 | 12.09 | | 6.11 | | | | | | | | | | | | | [37] |
| | 2002 | 68.17 | 1.26 | 10.12 | 2.91 | 13.26 | | 5.31 | | | | | | | | | | | | | [38] |
| | 2003 | 65.90 | 1.21 | 9.23 | 2.70 | 13.33 | | 5.97 | | | | | | | | | | | | | [39] |
| | 2005 | | | | | | | | | | | | 55.75 | 7.54 | 34.57 | 1.87 | 0.27 | | 6650 | | [15] |
| Shaoxing | 1999 | 50.00 | 1.50 | 4.10 | 2.80 | 5.10 | 0.03 | 33.87 | | | | | 53.96 | 7.67 | 36.21 | 1.82 | 0.35 | | 3093 | | [21] |
| Shenyang | 2000 | | | | | | | | | | | | 57.90 | 8.06 | 32.18 | 1.56 | 0.29 | | 8241 | | [21] |
| Shenzhen | 1994 | 40.00 | | 17.00 | 5.00 | 13.00 | 2.00 | 23.00 | 40.94 | 40.20 | 52.79 | 7.01 | 59.02 | 8.38 | 31.01 | 1.30 | 0.28 | | 7403 | 15,304 | [8,9] |
| | 1999 | 50.62 | 7.16 | 14.24 | 6.72 | 13.30 | | 7.96 | 49.91 | 21.24 | 68.30 | 10.46 | 57.25 | 7.86 | 33.19 | 1.39 | 0.30 | | 7754 | 19,246 | [21] |
| | 2008 | 51.10 | 5.90 | 8.40 | 6.90 | 14.70 | | 13.00 | | | | | | | | | | | | | [27] |
| Taiyuan | 2001 | | | | | | | | 41.78 | | | | 59.91 | 4.69 | 32.42 | 1.68 | 0.41 | 0.89 | 5743 | 12,127 | [28] |
| | 2003 | | | | | | | | 40.50 | | | | 56.95 | 5.82 | 33.96 | 1.65 | 0.71 | 0.91 | 6279 | 13,078 | [6] |
| Tianjin | 1996 | 53.90 | 1.10 | 5.88 | 0.80 | 4.10 | | 34.20 | | | | | | | | | | | | | [14] |
| | 2010 | 77.24 | 1.59 | 8.41 | 1.24 | 7.83 | | 3.69 | | | | | | | | | | | | | [40] |
| Wuhan | 1996 | 52.00 | 1.71 | 7.12 | 1.42 | 9.29 | 0.56 | 27.90 | 47.67 | 53.22 | 40.30 | 6.48 | 57.54 | 8.13 | 32.53 | 1.47 | 0.33 | | 4469 | 11,582 | [8,9] |
| | 1998 | 60.65 | 1.53 | 12.16 | 1.17 | 9.08 | | 15.45 | 53.51 | 38.08 | 53.21 | 8.70 | 56.25 | 7.91 | 34.18 | 1.39 | 0.28 | | 5186 | 15,019 | [21] |
| | 1999 | 57.44 | 0.90 | 5.06 | 1.15 | 9.51 | | 25.92 | 51.37 | 53.21 | 39.84 | 6.95 | 57.17 | 8.18 | 32.76 | 1.58 | 0.31 | | 4005 | 11,638 | [21] |
| | 2006 | 57.58 | 6.18 | 8.31 | 1.81 | 9.62 | | 16.50 | | | | | | | | | | | | | [41] |
| Wuhu | 1997 | 67.60 | | 4.00 | 0.60 | 1.70 | 3.60 | 22.50 | 55.99 | 52.78 | 40.67 | 6.54 | 55.07 | 7.76 | 34.55 | 2.05 | 0.57 | | 2863 | 10,400 | [8] |
| Xiamen | 1994 | 55.40 | 1.40 | 5.84 | 1.40 | 6.18 | | 25.50 | | | | | | | | | | | | | [14] |
| Xi'an | 1997 | 15.74 | 3.94 | 3.35 | 2.48 | 7.93 | | 66.56 | 24.95 | 76.76 | 20.03 | 3.21 | 55.25 | 8.43 | 34.54 | 1.26 | 0.52 | | 3363 | 5714 | [8,9] |
| Yanshan | 2000 | 51.83 | 5.75 | 5.43 | 2.97 | 10.37 | | 23.65 | 49.56 | | | | 50.90 | 8.54 | 35.74 | 1.20 | 1.15 | 2.48 | 5211 | 13,583 | [11] |
| N | | 79 | 69 | 79 | 79 | 79 | 12 | 79 | 29 | 22 | 22 | 22 | 35 | 35 | 35 | 35 | 35 | 5 | 37 | 24 | |
| Mean | | 55.86 | 2.94 | 8.52 | 3.16 | 11.15 | 0.84 | 18.36 | 48.12 | 43.57 | 49.06 | 7.38 | 56.99 | 7.84 | 33.05 | 1.55 | 0.38 | 1.27 | 5337 | 13,509 | |
| Min | | 15.74 | 0.83 | 2.83 | 0.60 | 1.70 | 0.02 | 1.36 | 24.95 | 20.56 | 20.03 | 3.21 | 50.90 | 4.69 | 25.06 | 0.96 | 0.14 | 0.89 | 2863 | 5714 | |
| Max | | 85.80 | 9.12 | 25.70 | 20.44 | 28.18 | 3.60 | 66.56 | 61.74 | 76.76 | 70.51 | 10.46 | 64.32 | 9.20 | 39.76 | 2.05 | 1.22 | 2.48 | 9436 | 19,246 | |

Remark:
C, carbon content; H, hydrogen content; O, oxygen content; N, nitrogen content; S, sulfur content; Cl, chlorine content; *M*, moisture content; *A*, ash content; *V*, volatile content; *FC*, fixed carbon content; $Q_{net}$, lower heating value (LHV); $Q_{gr}$, higher heating value (HHV); daf, dry ash free basis; w, wet basis; d, dry basis; *N*, number of samples.

inconsistent reporting causes errors in comparing the reported values [57].

(5) In the proximate and ultimate analysis and heating value results, the reports may present the terms as accepted basis, air dry basis, dry basis or dry ash-free basis. Although data of different bases can be transferred into each other, it is troublesome for comparison, especially lacking of moisture or some other basic data.

(6) Though there is an authoritative methodology in characterizing municipal solid waste [58], many data have not followed it and the scopes of each analysis were individually determined. This may explain why the compositions of waste, even among large cities show great variability.

(7) In the thermochemical research, some MSW samples are collected from real waste, while others are derived from clean or pure materials. There is a significantly difference on moisture and ash content in these two collecting methods. For biodegradable substances, the chemical composition will also change with time.

### 1.3. Common issues concerning waste composition in China

#### 1.3.1. The physical composition of MSW

MSW is a series of heterogeneous materials, whose chemical characteristics relate closely with the chemical properties of the various constituent components. Table 2 classifies MSW into two main categories on *Sampling and Analysis Methods for Domestic Waste* [58]: organics and inorganics. Organics include food residue, wood waste, paper, textiles, rubber, and plastic. Inorganics include ash, tiles, glass, metals, and other inert materials. Inorganics can be regarded as inert materials that do not impact on thermochemical reactions. Since rubber is categorized as a separate class in some regions of China, here six typical organic components, namely food residue, wood waste, paper, textiles, plastics, and rubber, are focused upon.

#### 1.3.2. Factors that influence MSW composition

The physical composition of MSW varies across climate, lifestyle, economic status and region [59–61], as shown in Table 3. In developed regions with high living standards, the MSW contains more plastics, paper, and textiles. In regions with coal-based heating system, MSW contains more inorganic components, especially during winter (the heating season) [61]. Over the past few years, with MSW generation in China increasing tremendously, the composition of the waste has changed greatly. The percentage of inorganic matters has decreased and the percentage of organic components has increased gradually, which indicated that the combustibles increased and the feasibility of waste incineration improved [16].

### 1.4. Relationship between MSW fuel characteristics and its physical components

Energy production depends on the composition of MSW, particularly paper and plastics [59]. To evaluate the feasibility of energy recovery as an integral part of solid waste management system, it is of great importance to determine its proximate and ultimate analysis and heating value [62].

For coal or biomass, the results of proximate, ultimate analysis and HV can represent the overall situation of the samples. However, the sample mass for ultimate analysis is only 1–5 mg

**Table 2**
The physical classification of MSW.

| Physical classification | Explanation |
|---|---|
| Organics | |
| Food residue | Rice, food residue, meat, vegetables, fruit |
| Wood waste | Waste wood, one-off chopsticks, bamboo, flowers, grass, leaves, branches |
| Paper | Tetrapack packaging, cardboard, office paper, toilet paper, newsprint, magazines |
| Textiles | Clothes, cloth shoes, cotton, chemical fiber |
| Plastics | Plastic film, plastic bottles, tubes, polyethylene bag, plastic toys |
| Rubber | Rubber shoes, waste tires |
| Inorganics | |
| Metals | Iron wire, cans, metal parts, pans |
| Glass | Glass fragments, glass bottles, mirrors, glass balls |
| Tiles | Stones, tiles, cement, ceramic |
| Ash | Slag, soil |
| Other | Batteries, plaster |

**Table 3**
Factors that influence the composition of the waste.

| Factors | Characteristics |
|---|---|
| Region | |
| Residential area (gas-based heating system) | High food residue fraction, little ash, high moisture content, high combustible fraction, high HV |
| Residential area (coal-based heating system) | High ash content, low combustible fraction, low HV |
| Commercial area | High plastics and paper fraction, low ash content, low moisture content, high HV |
| Office area | Lower plastics and paper than commercial area, approximate moisture content with residential area (gas-based heating system), higher HV than residential area (gas-based heating system) |
| Streets and roads | High ash content, low moisture content, higher HV than residential area (gas-based heating system) |
| Railway waste | High food waste fraction, high combustible fraction, high HV |
| Season | |
| Summer | High moisture content |
| Other seasons | Low moisture content |

**Table 4**
Summary of empirical models used for predicting the energy content of MSW from physical compositions.

| Regions | Equations | Basis | Num. | Reference |
|---|---|---|---|---|
| 35 countries | LHV = (23(Fo + 3.6 Pa) + 160(Pl + Ru) × 2.326 | Dry basis | (1) | [68] |
| Taiwan | LHV = (2229.91 + 7.90 Pa + 28.16Pl + 4.87 Ga–37.28*M*) × 4.186 | Dry basis | (2) | [69] |
| China | LHV = 41.1(Pl + Ru) + 22.9Fo + 20.7 Pa − 4.5*M* | Dry basis | (3) | [8] |
| China | LHV = [458.0Pl + 141.1(Te + Fo + Pa + Wo) + 8.2A](100-M)/100 − 25(*M* + 9H) | Dry basis | (4) | [70] |
| Taiwan | LHV = [(35.19 Pa + 71.17Pl + 36.24Te + 48.06Wo + 42.21Fo + 44Mi)(100 − *M*)/100 − 6*M*] × 4.186 | Dry basis | (5) | [62] |
| Taiwan | LHV = ((47.3 Pa + 58.6Pl + 38.6Te + 32.4Wo + 45.2Fo + 62.3Ru + 50.1Mi) (100 − *M*)/100 − 6*M*) × 4.186 | Dry basis | (6) | [71] |
| Taiwan | LHV = (22.1 Pa + 28.1Pl + 24.6Te + 12.7Wo + 6.0Fo + 57.4Ru + 17.2Mi) × 4.186 | Wet basis | (7) | [71] |
| Jordan | HHV = (267.0(Pl/Pa) + 2285.7) × 4.186 | Dry basis | (8) | [72] |
| Malaysia | HHV = 112.157Fo + 183.386 Pa + 288.737Pl + 5064.701 | Wet basis | (9) | [57] |

Remark:
LHV, kJ/kg; HHV, kJ/kg; Pa, Paper, wt%; Pl, Plastic, wt%; Ga, Garbage (e.g. food, textiles, garden wastes), wt%; Te, Textiles, wt%; Wo, wood, wt%; Fo. food, wt%; Ru, rubber, wt%; Mi, miscellaneous component, wt%; *M*, wt%; *A*, wt%; H, wt%.

and the sample mass for proximate analysis and HV measurement is about 1 g [63–67], which is inadequate in consideration of the vast variance in MSW compositions [57]. Nevertheless, it is difficult to increase sample quantity in the measurements on current calibrated apparatuses. Therefore, it is worthwhile to predict the chemical composition and HV of MSW from its physical composition.

There is no report on method predicting the proximate and ultimate compositions of MSW. Some equations to predict the HV of waste from physical composition were proposed in previous studies, as Table 4 shows. Eqs. (1)–(6) and (8) predicted LHV, and the others predicted HHV. For unification, the unit of HV was transferred to kJ/kg in equations.

### 1.5. The aim of this paper

Here, we try to review the physical classification, proximate and ultimate analysis and heating value of MSW in typical cities and those of main MSW components in China. Furthermore, we focus on predicting the proximate and ultimate analysis results based on physical compositions and developing a non-dewatered physical components model for heating value prediction.

## 2. Characteristics of MSW in typical Chinese cities

### 2.1. Physical composition

Fig. 1 shows the mean physical composition of MSW in Chinese cities. The average physical combustible and non-combustible fractions of the MSW were 81.64% and 18.36%, respectively. In combustible MSW, the contents of food residue, plastics, paper, textiles, wood waste and rubber, in decreasing order, were 55.86%, 11.15%, 8.52%, 3.16%, 2.94% and 0.84%. The fluctuations of physical components are shown in Fig. 2. The amount of food residue and non-combustibles had a wide range of distribution. Food residue prevailed in the MSW category. Due to the high moisture content of food residue, the moisture of Chinese MSW was usually very high. The rubber fraction in waste was very low, thus rubber was combined with plastics in some statistics.

### 2.2. Thermochemical properties

As Table 1 shows, the average moisture of 30 MSW samples was 48.12%, with large fluctuations. The highest was 61.74%, and the lowest was also as high as 24.95%. Usually, the moisture content of MSW in China is much higher than that in European and American countries, which is only about 10–30% [74]. It may be due to the differences in climate and life style. Therefore, torrefaction of Chinese MSW is of great importance before

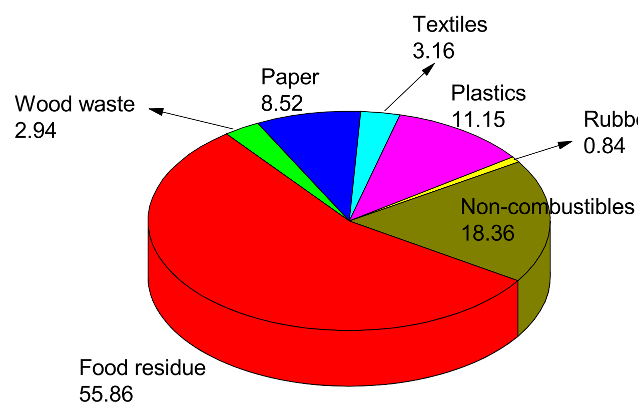


**Fig. 1.** The mean physical composition of MSW.

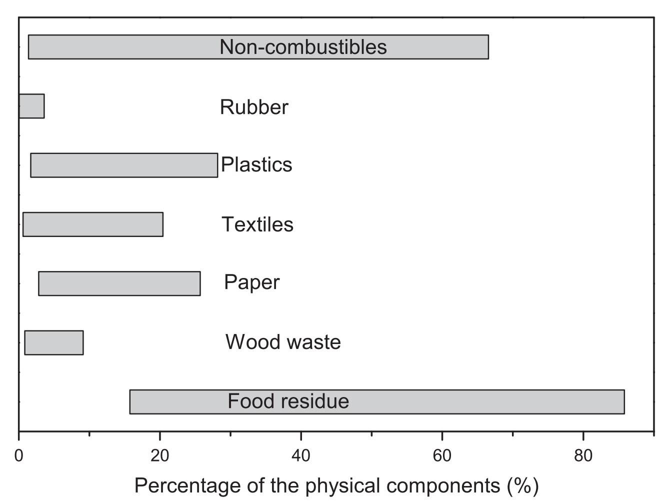


**Fig. 2.** The fluctuations of physical components of MSW.

incineration, pyrolysis and gasification. The average ash content in MSW was 43.57%, derived from glass, ash, soil, ceramic and tiles in MSW. However, the ash content of MSW fluctuated greatly, from 20.56% to 76.76%, which was related to local economics and heating system. The results of ash content indicated that waste classification was needed in China for better use of MSW as a fuel. The FC content of MSW was very low, due to the high ash content and the high volatiles in MSW.

Carbon, oxygen and hydrogen were the major organic fractions, while nitrogen, sulfur and chlorine were the minor ones. The mean carbon content of MSW was 56.99%, and the H content

of MSW was 7.84%. Only few literatures reported the Cl content in MSW, which was relatively high compared to other fuels, such as coal and biomass. The Cl in MSW was presented as two major forms: one was inorganic chlorine, mainly from the salt in food residue; the other form was organic chlorine, from plastics and rubber.

As shown in Table 1, the average LHV of Chinese MSW was 5337 kJ/kg with large fluctuations. The highest was that of Macao waste in 1992, as high as 9436 kJ/kg, and the lowest was that of Xi'an waste in 1997, only 2810 kJ/kg. It indicated that some solid waste in China needed auxiliary fuels to incinerate. The range of the LHV of MSW in Korea was 11.0–12.2 MJ/kg [59] and the LHV of Malaysian waste was 9125 kJ/kg [60]. It showed that the LHV of MSW in China was much lower than that of MSW in other Asian counties. The mean HHV of Chinese waste was 13,509 kJ/kg, more than two times of the LHV, which indicated that moisture was a key factor restricting waste incineration in China.

## 3. The chemical characteristics of components of MSW

As shown in Table 2, this paper focuses on six categories of typical organic components, namely food residue, wood waste, paper, textiles, plastics, and rubber. The original data are shown in Appendix and the statistical results of the proximate and ultimate analysis and HHV of these six components are shown in Table 5. *N* stands for number of data. To analyze the characteristics of MSW in China, mean and standard deviation (stdev) were introduced as statistical indexes. The coefficient of variation (CV) is also useful to compare the variability of variables that have different standard deviation and different means, which can be determined by the following equation [73]:

$$CV = \frac{\text{stdev}}{\text{avg}} \times 100\% \tag{10}$$

Descriptive statistics, such as *t*-test statistics, is used to show the 95% confidence interval of the incidence of a particular factor of the MSW [74]. The 95% confidence interval (CI) is composed of both lower bound (LB) and upper bound (UB) of each characteristic.

### 3.1. Food residue

As shown in Table 5, the average moisture content of food residue was extraordinary high (69.85%), and the confidence interval was narrow, because food residue was consisted of many high moisture components, such as vegetables and fruit peel. Average ash content as dry basis of food residue was 20.98%, lower than that of MSW. The mean volatile matter of food residue was as high as 66.79%.

The elemental composition of food waste followed the sequences: C > O > H > N > Cl > S. The average C content was 47.22% and the confidence interval was narrow. The average H content was 7.04%, and it varied greatly with samples, from 3.10% to 18.45%. The N content of food residue was as high as 3.86%, because meat, fruit and vegetables contained a high content of proteins [75]. The Cl content of food residue was also very high, mainly because of salt.

The average HHV of food residue was 15,386 kJ/kg as dry basis, a little higher than the average value of MSW. The HHV of food residue varied greatly, because of the complexity of the sub-components of food residue in China.

### 3.2. Wood waste

As shown in Table 5, the average moisture content of wood waste was lower than that of food residue. The average ash content of wood waste was 6.84%, and the confidence interval was very narrow.

The C, H and O content of wood waste had a narrow CI, because the components of wood waste were simple and the difference among each component was tiny.

The average HHV of wood waste was 19,461 kJ/kg, higher than that of food waste, mainly because of lower ash content.

### 3.3. Paper

The average moisture of paper is 13.15%, which is relatively high for pure paper. The reason was that some paper samples from the real waste [76–78] was in contact with high moisture content such as food residue and was impacted by rain or snow.

The average C, H and O content of paper was 45.62%, 6.01% and 47.78%, respectively, which was similar to the content of cellulose ($(C_6H_{10}O_5)_n$), a primary constituent of paper [75]. The CI of the ultimate analysis of paper was very narrow, which indicated that the elemental composition of different paper samples was identical.

The average HHV of paper was 15,894 kJ/kg, but varied tremendously from 13,445 kJ/kg to 19,277 kJ/kg, due to the sampling of different research.

### 3.4. Textiles

As shown in Table 5, similar to paper, the moisture of textiles varied from sample to sample, and the mean value was 13.75%. The average ash content of textiles was lower than that of food residue, wood waste and paper, which indicated that artificial polymers contained less ash than natural polymers. The CIs of the elements were very narrow; it can be further concluded that the elemental composition of the textile was very close. The HHV of textiles was relatively high, due to the low ash content. Without moisture interference, the HHV of textiles was of few fluctuations.

### 3.5. Plastics

According to their different ingredients, plastics can be divided into chlorine-free plastics (PE, PP, PS, etc.) and chlorinated plastics (PVC). As elucidated in Section 1.2 (4), the data of plastics with unknown ingredients were not cited in this paper.

#### 3.5.1. Chlorine-free plastics

As shown in Table 5, for chlorine plastics, the proximate analysis also showed consistency. The percentage of volatile matter was nearly 100% and that of moisture, ash and fixed carbon was extremely low. The elements were mainly C and H; the content of O, N and S was scarce and the Cl content was zero. The CIs of elements were very narrow, which indicated that different kinds of chlorine-free plastics had similar elemental composition. The mean HHV of chlorine-free plastics was 43,448 kJ/kg and the lower bound was also more than 35,000 kJ/kg.

#### 3.5.2. Chlorinated plastics (PVC)

As shown in Table 5, just like the chlorine-free plastics, PVC contained little moisture, while the volatile matter content was very high. Different from chlorine-free plastics, PVC contained some ash and fixed carbon. The ash content of PVC varied considerably. The main elements were C, H and Cl, and the CIs were relatively narrow. The mean HHV of PVC was 21,172 kJ/kg, approximately a half of that of chlorine-free plastics. The reason was that the Cl content of PVC was about 50%, and it could be further evidenced that plastics with or without chlorine should be separated as possible.

**Table 5**
The proximate analysis, ultimate analysis and HHV of Chinese MSW.

| Components | Statistical items | Proximate analysis (wt%) | | | | Ultimate analysis (wt%) | | | | | | $Q_{gr,d}$ (kJ/kg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $M_w$ | $A_d$ | $V_d$ | $FC_d$ | $C_{daf}$ | $H_{daf}$ | $O_{daf}$ | $N_{daf}$ | $S_{daf}$ | $Cl_{daf}$ | |
| Food residue | *N* | 12 | 23 | 23 | 23 | 20 | 20 | 20 | 20 | 19 | 5 | 9 |
| | Mean | 69.85 | 20.98 | 66.79 | 12.23 | 47.22 | 7.04 | 41.15 | 3.86 | 0.49 | 1.06 | 15,386 |
| | Min | 54.51 | 2.74 | 45.50 | 0.04 | 32.81 | 3.10 | 26.54 | 0.82 | 0.13 | 0.12 | 9643 |
| | Max | 89.09 | 42.00 | 87.30 | 24.94 | 59.95 | 18.45 | 59.93 | 7.75 | 1.10 | 2.50 | 20,107 |
| | Stdev | 10.87 | 12.30 | 11.46 | 5.05 | 7.08 | 3.53 | 8.24 | 1.88 | 0.27 | 0.95 | 3841 |
| | CV(%) | 15.6 | 58.6 | 17.2 | 41.3 | 15.0 | 50.2 | 20.0 | 48.8 | 55.5 | 89.7 | 25.0 |
| | 95% CI | | | | | | | | | | | |
| | LB | 62.94 | 15.66 | 61.83 | 10.05 | 43.90 | 5.39 | 37.29 | 2.97 | 0.36 | 0.00 | 12,433 |
| | UB | 76.76 | 26.30 | 71.74 | 14.42 | 50.53 | 8.70 | 45.00 | 4.74 | 0.62 | 2.23 | 18,339 |
| Wood waste | *N* | 8 | 6 | 6 | 6 | 9 | 9 | 9 | 9 | 7 | 1 | 5 |
| | Mean | 42.95 | 6.84 | 75.87 | 17.29 | 51.35 | 6.39 | 40.50 | 1.59 | 0.18 | 0.29 | 19,461 |
| | Min | 20.00 | 1.35 | 71.20 | 11.95 | 45.87 | 5.65 | 33.64 | 0.20 | 0.00 | 0.29 | 16,251 |
| | Max | 60.00 | 12.95 | 80.64 | 21.71 | 57.18 | 7.30 | 47.49 | 3.56 | 0.33 | 0.29 | 21,621 |
| | Stdev | 16.01 | 4.10 | 3.59 | 3.25 | 3.74 | 0.48 | 4.69 | 1.16 | 0.13 | | 2300 |
| | CV(%) | 37.3 | 59.9 | 4.7 | 18.8 | 7.3 | 7.5 | 11.6 | 73.1 | 69.7 | | 11.8 |
| | 95% CI | | | | | | | | | | | |
| | LB | 29.56 | 2.54 | 72.11 | 13.88 | 48.48 | 6.01 | 36.90 | 0.69 | 0.06 | | 16,605 |
| | UB | 56.34 | 11.13 | 79.64 | 20.70 | 54.22 | 6.75 | 44.11 | 2.48 | 0.30 | | 22,317 |
| Paper | *N* | 24 | 22 | 22 | 22 | 22 | 22 | 22 | 22 | 20 | 4 | 13 |
| | Mean | 13.15 | 12.20 | 76.14 | 11.66 | 45.62 | 6.01 | 47.78 | 0.34 | 0.22 | 0.28 | 15,894 |
| | Min | 1.39 | 1.18 | 61.47 | 2.94 | 38.29 | 1.31 | 42.35 | 0.03 | 0.02 | 0.10 | 13,445 |
| | Max | 50.23 | 35.35 | 85.46 | 23.79 | 49.60 | 7.09 | 54.54 | 1.74 | 0.86 | 0.73 | 19,277 |
| | Stdev | 15.70 | 8.87 | 6.89 | 5.03 | 2.94 | 1.13 | 3.41 | 0.36 | 0.18 | 0.30 | 1551 |
| | CV(%) | 119.4 | 72.8 | 9.0 | 43.1 | 6.4 | 18.7 | 7.1 | 104.3 | 85.3 | 106.6 | 9.8 |
| | 95% CI | | | | | | | | | | | |
| | LB | 6.52 | 8.26 | 73.09 | 9.43 | 44.32 | 5.51 | 46.27 | 0.18 | 0.13 | 0.00 | 14,957 |
| | UB | 19.77 | 16.13 | 79.20 | 13.89 | 46.92 | 6.51 | 49.29 | 0.50 | 0.30 | 0.76 | 16,832 |
| Textiles | *N* | 18 | 16 | 16 | 16 | 20 | 20 | 20 | 20 | 20 | 4 | 11 |
| | Mean | 13.75 | 3.56 | 82.69 | 13.75 | 54.08 | 5.84 | 38.09 | 1.70 | 0.22 | 0.36 | 20,162 |
| | Min | 0.17 | 0.34 | 73.65 | 8.87 | 45.30 | 2.86 | 31.98 | 0.08 | 0.00 | 0.06 | 17,607 |
| | Max | 60.33 | 9.33 | 89.57 | 18.70 | 63.46 | 7.76 | 47.60 | 4.72 | 0.43 | 0.89 | 23,080 |
| | Stdev | 18.98 | 3.36 | 5.09 | 2.79 | 5.00 | 1.21 | 4.96 | 1.45 | 0.14 | 0.38 | 2102 |
| | CV(%) | 138.0 | 94.5 | 6.2 | 20.3 | 9.2 | 20.8 | 13.0 | 84.9 | 65.2 | 107.8 | 10.4 |
| | 95% CI | | | | | | | | | | | |
| | LB | 4.31 | 1.77 | 79.98 | 12.27 | 51.75 | 5.27 | 35.77 | 1.03 | 0.15 | 0.00 | 18,750 |
| | UB | 23.18 | 5.35 | 85.40 | 15.24 | 56.42 | 6.41 | 40.41 | 2.38 | 0.28 | 0.96 | 21,574 |
| Chlorine-free plastics | *N* | 25 | 24 | 24 | 24 | 34 | 34 | 34 | 34 | 34 | 21 | 13 |
| | Mean | 0.13 | 0.48 | 99.44 | 0.08 | 86.22 | 12.97 | 0.73 | 0.08 | 0.05 | 0.00 | 43,448 |
| | Min | 0.00 | 0.00 | 97.41 | 0.00 | 83.75 | 7.68 | 0.00 | 0.00 | 0.00 | 0.00 | 35,725 |
| | Max | 0.57 | 2.59 | 100.00 | 0.60 | 92.14 | 15.23 | 5.30 | 0.70 | 0.37 | 0.00 | 47,285 |
| | Stdev | 0.16 | 0.61 | 0.60 | 0.17 | 1.77 | 2.15 | 1.23 | 0.15 | 0.09 | | 3858 |
| | CV (%) | 125.5 | 126.6 | 0.6 | 218.7 | 2.1 | 16.6 | 167.1 | 196.1 | 187.1 | | 8.9 |
| | 95% CI | | | | | | | | | | | |
| | LB | 0.06 | 0.22 | 99.19 | 0.01 | 85.60 | 12.22 | 0.31 | 0.03 | 0.12 | 0.00 | 41,117 |
| | UB | 0.19 | 0.73 | 99.7 | 0.15 | 86.84 | 13.72 | 1.16 | 0.13 | 0.08 | 0.00 | 45,779 |
| PVC | *N* | 15 | 14 | 14 | 14 | 16 | 16 | 16 | 16 | 16 | 16 | 9 |
| | Mean | 0.21 | 4.18 | 85.94 | 9.87 | 40.59 | 5.00 | 0.59 | 0.08 | 0.20 | 53.53 | 21,172 |
| | Min | 0.00 | 0.00 | 65.06 | 4.54 | 36.83 | 4.25 | 0.00 | 0.00 | 0.00 | 42.37 | 15,876 |
| | Max | 0.78 | 14.99 | 95.46 | 20.47 | 52.3 | 5.83 | 5.30 | 0.23 | 1.25 | 58.15 | 22,735 |
| | Stdev | 0.19 | 6.07 | 11.24 | 5.40 | 3.80 | 0.47 | 1.43 | 0.08 | 0.32 | 4.32 | 2180 |
| | CV (%) | 89.4 | 145.1 | 13.1 | 54.7 | 9.4 | 9.4 | 241.6 | 91.8 | 162.0 | 8.1 | 10.3 |
| | 95% CI | | | | | | | | | | | |
| | LB | 0.11 | 0.68 | 79.45 | 6.76 | 38.56 | 4.75 | 0.00 | 0.04 | 0.03 | 51.23 | 19,497 |
| | UB | 0.31 | 7.69 | 92.43 | 12.99 | 42.61 | 5.25 | 1.35 | 0.13 | 0.37 | 55.83 | 22,848 |
| Rubber | *N* | 28 | 26 | 26 | 26 | 24 | 24 | 24 | 24 | 24 | 2 | 15 |
| | Mean | 0.89 | 15.64 | 64.70 | 19.67 | 84.52 | 8.62 | 4.31 | 0.86 | 1.56 | 1.62 | 29,789 |
| | Min | 0.00 | 3.33 | 42.75 | 2.27 | 74.9 | 6.70 | 0.00 | 0.00 | 0.00 | 1.16 | 21,812 |
| | Max | 2.00 | 43.62 | 86.15 | 32.97 | 89.53 | 13.26 | 14.52 | 2.42 | 4.17 | 2.08 | 38,868 |
| | Stdev | 0.54 | 12.15 | 9.97 | 9.69 | 4.14 | 1.81 | 4.04 | 0.65 | 0.84 | 0.65 | 6211 |
| | CV (%) | 61.0 | 77.7 | 15.4 | 49.3 | 4.9 | 21.0 | 93.9 | 74.8 | 53.7 | 40.2 | 20.8 |
| | 95% CI | | | | | | | | | | | |
| | LB | 0.68 | 10.73 | 60.67 | 15.75 | 82.77 | 7.86 | 2.60 | 0.59 | 1.20 | | 26,349 |
| | UB | 1.10 | 20.54 | 68.72 | 23.58 | 86.27 | 9.38 | 6.01 | 1.14 | 1.91 | | 33,228 |

### 3.6. Rubber

As shown in Table 5, the moisture of rubber was low, while the ash, volatile matter, and fixed carbon showed uncertainty. The C and H content of rubber were lower than that of chlorine-free plastics. The O content of rubber varied greatly; some research detected no oxygen, while some research reported the O content was more than 10%. It was noteworthy that the S content of rubber was very high, because that vulcanization usually took place during the production of rubber. The Cl content of rubber was also high, because of chloroprene rubber. The HHV of different rubbers varied sharply from 21,812 to 38,868 kJ/kg. The average

HHV of rubber was 29,789 kJ/kg, between that of PVC and chlorine-free plastics.

## 4. The prediction of proximate analysis, ultimate analysis and heating value of mixed MSW from physical composition

### 4.1. The prediction of proximate analysis and ultimate analysis from physical composition

Based on the physical and chemical properties analyzed above, a method was proposed to predict the chemical properties of waste from physical composition. The properties of food residue, wood waste, paper, textiles, and rubber were estimated by the average value. Since the characteristics of chlorine-free plastics differed greatly from those of PVC, as has been mentioned above, chlorine-free plastics and PVC should be separated using sample methods during waste physical sorting [58] to gain a PVC fraction (PVCF). Since plastics were not divided to that with or without chlorine, 13% of the total plastics were assumed as the typical PVC fraction in China according to the statistical research [79]. Thus, the properties of plastics could be obtained by the following weighted equations:

$$F_{\text{plastics}} = \text{PVCF} \times F_{\text{PVC}} + (1-\text{PVCF})F_{\text{chlorine-free plastics}} \tag{11}$$

Because of the influence of rain or snow, the actual waste moisture content is often higher than the moisture predicted based on the physical composition. For this reason, a supplementary moisture coefficient (SMC) was introduced, which was defined as the increased moisture content due to rainfall and other factors. In this case, the actual moisture content could be estimated by the sum of the moisture calculated from physical composition and SMC. The elemental composition, *V* and *FC* could be estimated by the combustibles. The ash content could be estimated by the sum of that calculated from combustibles and non-combustibles. Because MSW physical composition was usually reported as wet basis, the items were transferred to wet basis during prediction. After that, the data were transferred to the form as Table 1 for comparison:

$$M_{\text{MSW,ar}} = (1-\text{SMC})\sum_i c_i M_{i,\text{ar}} + \text{SMC} \tag{12}$$

$$A_{\text{MSW,ar}} = (1-\text{SMC})\left(u + \sum_i c_i A_{i,\text{ar}}\right) \tag{13}$$

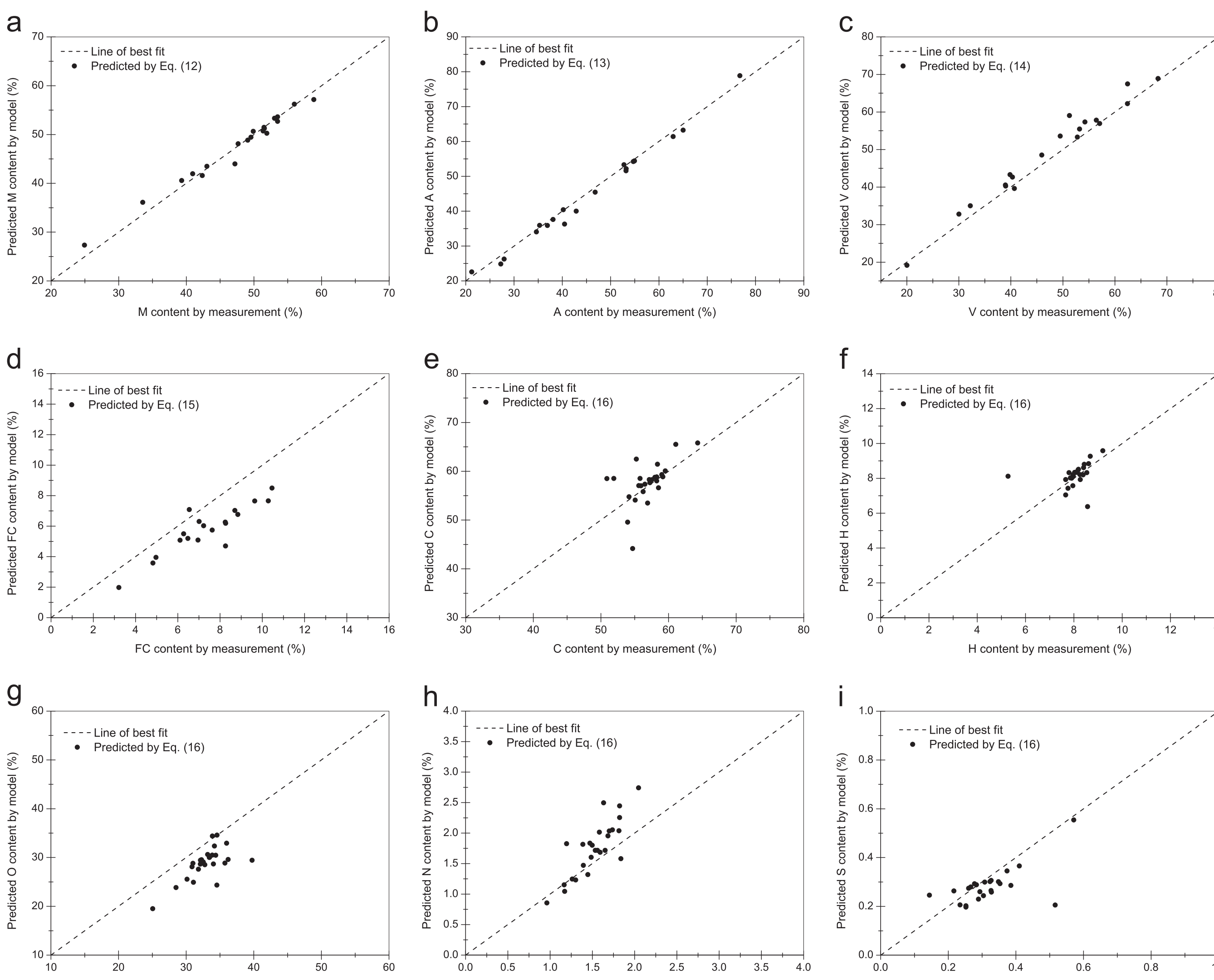


**Fig. 3.** Comparisons of proximate and ultimate analysis from measurement and predictions based on physical components: (a) *M*, (b) *A*, (c) *V*, (d) *FC*, (e) C, (f) H, (g) O, (h) N, and (i) S.

**Table 6**
The MAEs and max errors of proximate and ultimate analysis results from predictions based on physical components.

| Parameters | Proximate analysis | | | | Ultimate analysis | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $M_w$ | $A_d$ | $V_d$ | $FC_d$ | $C_{daf}$ | $H_{daf}$ | $O_{daf}$ | $N_{daf}$ | $S_{daf}$ | $Cl_{daf}$ |
| *N* | 20 | 19 | 19 | 19 | 26 | 26 | 26 | 26 | 26 | 2 |
| MAE (wt%) | 0.94 | 1.39 | 2.30 | 1.62 | 2.45 | 0.46 | 4.17 | 0.28 | 0.12 | 0.77 |
| Max error (wt%) | 3.23 | 4.20 | 7.76 | 3.56 | 10.53 | 2.84 | 10.32 | 0.86 | 0.88 | 1.39 |

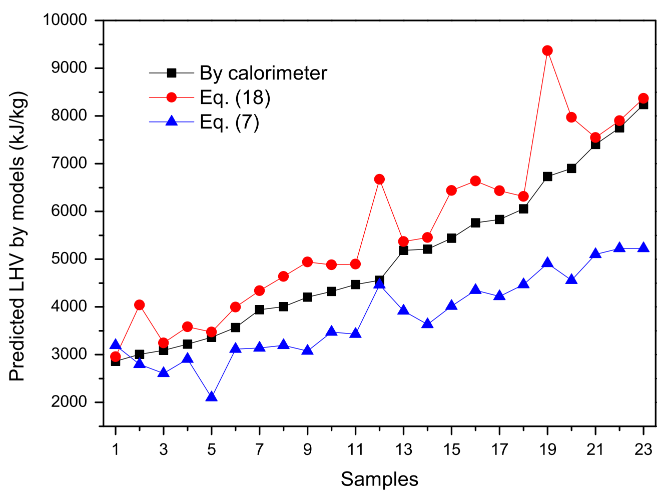


**Fig. 4.** LHV of wet basis from different models.

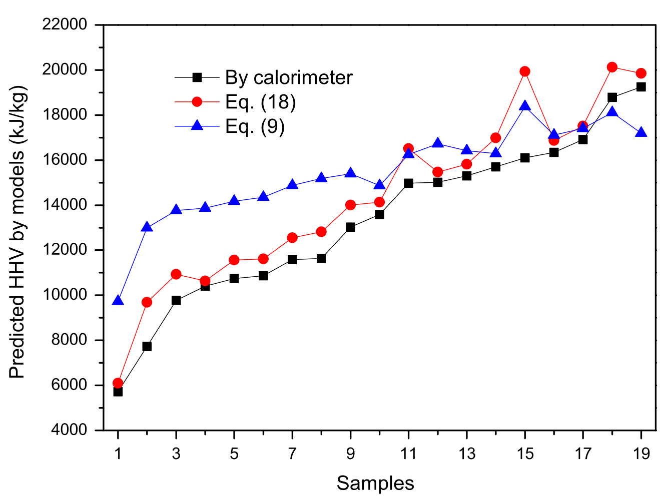


**Fig. 5.** HHV of dry basis from different models.

$$V_{MSW,ar} = (1 - SMC)(\sum_i c_i V_{i,ar}) \tag{14}$$

$$FC_{MSW,ar} = (1 - SMC)(\sum_i c_i FC_{i,ar}) \tag{15}$$

$$E_{MSW,ar} = (1 - SMC)(\sum_i c_i E_{i,ar}) \tag{16}$$

where $c_i$ and $u$ represent the fraction of combustibles and non-combustibles, respectively, and $E$ represents elements content.

26 groups of MSW data whose information was complete were selected from Table 1 to calculate. The mean absolute error (MAE) was used as an index to evaluate the difference between the calculation and measurement:

$$\text{MAE} = \frac{\sum_{i=1}^{N} |F_{p,i} - F_{m,i}|}{N} \tag{17}$$

where $F_p$ and $F_m$ represent predicted and measured result, respectively.

To minimum MAE of moisture content, SMC was set as 0.16 to increase moisture content by 16% due to factors such as rainfall or snow. The comparisons of prediction and measurement of proximate and ultimate analysis results are shown in Fig. 3. Because there were only two groups of data of Cl content, they were not plotted here.

As shown in Fig. 3, prediction results and measured results fit surprisingly well, especially for M, A, C, H and S. The predictions of FC and O were a little lower than that of the measured values, while the predictions of V and N were a little higher than that of the measured values.

The MAEs and max errors are shown in Table 6. In considering the SMC, the MAE of 20 groups of data was only 0.94% and the max error was 3.23%, which was very low taking account of the mean moisture content of Chinese waste (47.95%). For *A*, *V* and *FC*, the predicted and measured results also fitted well; the MAEs were 1.31%, 2.19% and 1.57%, respectively. The MAE of C was only 2.45%, which was very low allowing for the average C content of Chinese waste (56.99%). Changchun waste in 2000 had the max error of C, which was 10.53%. The predictions of H also had good result; the MAE was 0.46% and the max error was 2.84%. The MAEs of O, N and S were 4.11%, 0.25% and 0.12%, respectively. It was worth noting that most research did not measure Cl content, due to the complexity of measurement. However, the predictions from physical composition showed that the Cl content in Chinese waste were between 1.08% and 4.06%, which remedied the difficulty of Cl measurement.

From the analysis above, it is feasible to predict the proximate and ultimate analysis from physical composition and the prediction model in this paper fitted well with the measured results, which remedied the disadvantages of the measurement of proximate and ultimate analysis.

### 4.2. The prediction of HV from waste physical composition

Because Chinese waste was sorted based on wet basis, $Q_{net,w}$ was adopted when prediction, and then $Q_{gr,d}$ could be calculated. The key assumption was that the inert material would not add or remove heat in the combustion process [74]. The LHV was determined by subtracting the latent heat of vaporization of SMC from the LHV weighting calculated from combustibles and described as

$$Q_{MSW,net,w} = (1 - SMC)\left(\sum_i c_i Q_{i,net,w}\right) - SMC \times \Delta h_v \tag{18}$$

where $\Delta h_v$ is the latent heat of vaporization of water at normal pressure.

Eqs. (1)–(6) and (8) were based on dry basis of MSW, which needed the data of physical components without moisture. Only

**Table 7**
The comparison of HV predicted by Eq. (18) with the experimental results and other models.

| Parameters | $Q_{net,w}$ | | $Q_{gr,d}$ | |
|---|---|---|---|---|
| Prediction methods | Eq. (18) | Eq. (7) | Eq. (18) | Eq. (9) |
| $N$ | 23 | 23 | 19 | 19 |
| MAE (%) | 13.0 | 22.9 | 8.2 | 22.6 |
| Max error (%) | 46.3 | 37.5 | 25.2 | 70.3 |

Eqs. (7) and (9) were based on wet basis of waste. The results from Eq. (18) were compared with those from Eqs. (7) and (9), as shown in Figs. 4 and 5. Through the comparison of LHV predicted by the model and Eq. (7), as shown in Fig. 4, Eq. (7) underestimated the LHV of MSW, while Eq. (18) overestimated the LHV. Fig. 5 shows the comparison of HHV predicted by Eqs. (18) and (9). The HHV predicted by Eq. (18) matched very well with measured values, while Eq. (9) always overestimated the HHV of MSW. This implied that the models based on the MSW of other regions did not apply to Chinese MSW.

Table 7 shows the mean absolute percentage errors and max percentage errors of different models. The model proposed in this paper showed a precision superior to Eqs. (7) and (9). This implied that estimating the LHV and HHV of Chinese MSW by Eq. (18) is a viable alternative.

## 5. Conclusions

The physical components of Chinese MSW followed the decreasing sequence that food residue > non-combustibles > plastics > paper > textiles > wood waste > rubber. Food residue and non-combustibles in waste had large fluctuations, while the fraction of rubber was very low. The LHV of Chinese MSW was much lower than the waste LHV of countries nearby.

The mean elementary H, O and N content in food residue varied greatly with samples. Conversely, the components of wood waste were simple and the difference among each component was small. The elemental composition of paper was simple, and similar to the content of cellulose. The elemental composition of textiles was also very close and the HHV of textiles was relatively high. Different kinds of chlorine-free plastics have similar properties. While the PVC shows different characteristics, and the mean HHV of PVC was about a half of that of chlorine-free plastics. It suggested that plastics with or without chlorine should be separated as possible. The S and Cl contents of rubber were relatively high, and the HHV of different rubbers varied sharply from 21,812 to 38,868 kJ/kg.

A novel model was proposed to predict the proximate and ultimate analysis results of MSW, and the PVC fraction in plastics and the supplementary moisture coefficient were introduced. The results showed that it was feasible to predict proximate and ultimate analysis results from physical composition and the predicted results fitted well with the measured ones, which remedied the disadvantages of the measurement of proximate and ultimate analysis. The HV could also be predicted from the physical composition of MSW, and the predicted results fitted well with the measured ones, too.

The chemical characteristics should be considered for thermal conversion process of Chinese MSW, such as the design of incinerator. Besides, the model that proposed in this paper can be utilized for prediction of proximate and ultimate composition and HV of Chinese MSW.

## Acknowledgments

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## Appendix

The proximate and ultimate analysis results and heating value of typical physical components of MSW in China.

| Components | Proximate analysis (wt%) | | | | Ultimate analysis (wt%) | | | | | | $Q_{gr,d}$(kJ/kg) | Reference used |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $M_w$ | $A_d$ | $V_d$ | $FC_d$ | $C_{daf}$ | $H_{daf}$ | $O_{daf}$ | $N_{daf}$ | $S_{daf}$ | $Cl_{daf}$ | | |
| Food residue | 89.09 | 13.57 | 69.66 | 16.77 | 32.81 | 4.77 | 59.93 | 2.35 | 0.13 | | | [80] |
| | 86.62 | 16.82 | 63.23 | 19.96 | 41.42 | 3.50 | 49.24 | 5.57 | 0.27 | | | [81] |
| | 78.12 | 2.74 | 87.30 | 9.96 | 52.40 | 6.91 | 32.42 | 7.75 | 0.52 | | 17,347 | [23] |
| | 72.00 | 16.00 | 72.36 | 11.64 | | | | | | | | [82] |
| | 71.64 | 27.54 | 62.83 | 9.63 | | | | | | | | [83] |
| | 70.00 | | | | 50.53 | 6.74 | 39.58 | 2.74 | 0.42 | | 13,917 | [84] |
| | 69.37 | 31.42 | 59.13 | 9.45 | | | | | | | | [83] |
| | 67.67 | | | | | | | | | | 12,582 | [76] |
| | 63.06 | 37.14 | 50.30 | 12.56 | | | | | | | | [77] |
| | 60.00 | | | | 51.38 | 7.31 | 36.82 | 3.24 | 0.17 | 1.09 | | [85] |
| | 56.12 | 37.74 | 54.97 | 7.29 | 56.50 | 6.68 | 31.07 | 4.08 | 0.40 | 1.27 | 9643 | [43] |
| | 54.51 | | | | 50.69 | 6.80 | 40.38 | 1.70 | 0.43 | | | [78] |
| | | 36.86 | 55.98 | 7.17 | 59.95 | 9.13 | 26.54 | 3.95 | 0.44 | | 17,927 | [46] |
| | | 9.71 | 77.97 | 12.32 | 52.24 | 7.30 | 34.35 | 4.97 | 1.01 | 0.12 | 19,796 | [86] |
| | | 16.92 | 68.03 | 15.05 | 50.09 | 5.08 | 37.14 | 6.58 | 1.10 | | 16,447 | [87] |
| | | 17.43 | 67.95 | 14.62 | 50.07 | 5.40 | 36.88 | 6.73 | 0.93 | | | [88] |
| | | 12.31 | 72.66 | 15.03 | 49.94 | 4.85 | 41.60 | 3.04 | 0.56 | | | [89] |
| | | 2.84 | 80.61 | 16.56 | 49.10 | 7.26 | 39.02 | 4.39 | 0.23 | | 20,107 | [90] |
| | | 16.00 | 72.35 | 11.65 | 48.50 | 14.20 | 35.80 | 1.30 | 0.20 | | | [91] |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 47.55 | 6.36 | 45.27 | 0.82 | | | | [92] |
| | | | | | 46.33 | 5.49 | 42.31 | 3.00 | 0.36 | 2.50 | | [15] |
| | | 15.40 | 70.87 | 13.73 | 43.25 | 6.38 | 47.47 | 2.43 | 0.47 | | | [52] |
| | | 9.25 | 83.30 | 7.45 | | | | | | | | [93] |
| | | 37.75 | 53.50 | 8.75 | 41.30 | 3.10 | 49.58 | 5.36 | 0.66 | | | [7] |
| | | | | | 35.60 | 5.20 | 55.80 | 2.60 | 0.50 | 0.30 | | [94] |
| | | 27.75 | 63.50 | 8.75 | 34.76 | 18.45 | 41.73 | 4.51 | 0.55 | | | [7] |
| | | 4.68 | 70.38 | 24.94 | | | | | | | | [95] |
| | | 33.23 | 51.23 | 15.53 | | | | | | | | [51] |
| | | 42.00 | 45.50 | 12.50 | | | | | | | 10,707 | [47] |
| | | 17.49 | 82.47 | 0.04 | | | | | | | | [96] |
| Wood waste | 60.00 | | | | 50.05 | 6.28 | 39.79 | 3.56 | 0.31 | | 21,148 | [97] |
| | 57.16 | 5.09 | 73.20 | 21.71 | | | | | | | | [83] |
| | 54.16 | 7.18 | 74.11 | 18.72 | | | | | | | | [83] |
| | 53.50 | | | | | | | | | | 16,251 | [98] |
| | 45.00 | | | | 51.84 | 6.52 | 39.04 | 1.98 | 0.33 | 0.29 | | [85] |
| | 29.93 | | | | 57.18 | 6.91 | 33.64 | 1.99 | 0.27 | | | [78] |
| | 23.85 | | | | | | | | | | 17,890 | [76] |
| | 20.00 | | | | 50.25 | 6.09 | 43.35 | 0.20 | 0.10 | | | [97] |
| | | 4.70 | 77.80 | 17.50 | | | | | | | | [82] |
| | | 9.76 | 78.28 | 11.95 | 55.09 | 7.30 | 36.60 | 0.86 | 0.15 | | 21,621 | [46] |
| | | 1.35 | 80.64 | 18.02 | 45.87 | 5.65 | 47.49 | 0.98 | 0.00 | | 20,395 | [99] |
| | | 12.95 | 71.20 | 15.85 | | | | | | | | [51] |
| | | | | | 46.71 | 6.14 | 46.27 | 0.88 | | | | [92] |
| | | | | | 50.83 | 6.26 | 42.13 | 0.68 | 0.10 | | | [100] |
| | | | | | 54.33 | 6.30 | 36.22 | 3.15 | | | | [92] |
| Paper | 50.23 | 9.48 | 76.55 | 13.96 | | | | | | | | [83] |
| | 48.33 | | | | | | | | | | 15,717 | [76] |
| | 48.07 | 9.24 | 75.93 | 14.83 | | | | | | | | [83] |
| | 34.70 | 21.78 | 64.17 | 14.06 | | | | | | | | [77] |
| | 25.92 | | | | 47.62 | 6.49 | 45.42 | 0.23 | 0.23 | | | [78] |
| | 11.19 | 1.18 | 83.39 | 15.43 | | | | | | | | [101] |
| | 10.25 | 2.33 | 82.95 | 14.72 | 41.20 | 6.13 | 52.37 | 0.10 | 0.19 | | | [102] |
| | 10.20 | | | | 46.17 | 6.17 | 47.13 | 0.32 | 0.21 | | 17,611 | [84] |
| | 8.44 | 10.20 | 76.62 | 13.18 | 46.97 | 5.12 | 47.69 | 0.15 | 0.07 | | 15,979 | [90] |
| | 7.29 | 2.61 | 73.6 | 23.79 | 49.02 | 6.31 | 42.35 | 1.74 | 0.38 | 0.19 | 16,833 | [43] |
| | 6.70 | 9.54 | 81.67 | 8.79 | 47.38 | 5.92 | 46.50 | 0.15 | 0.04 | | | [89] |
| | 6.61 | 20.19 | 72.32 | 7.48 | 46.14 | 7.06 | 46.17 | 0.25 | 0.38 | | 15,872 | [46] |
| | 6.49 | 9.47 | 78.19 | 12.33 | 46.66 | 6.25 | 46.86 | 0.13 | 0.09 | | 15,341 | [87] |
| | 6.05 | 9.61 | 77.53 | 12.86 | 47.40 | 6.45 | 45.97 | 0.12 | 0.07 | | | [88] |
| | 6.00 | | | | 46.28 | 6.38 | 46.81 | 0.32 | 0.21 | | 19,277 | [97] |
| | 5.44 | 26.08 | 66.96 | 6.97 | | | | | | | | [48] |
| | 4.85 | 10.05 | 80.50 | 9.45 | 40.46 | 6.31 | 52.56 | 0.34 | 0.33 | | | [81] |
| | 4.11 | 23.43 | 69.24 | 7.33 | 49.60 | 6.16 | 43.43 | 0.61 | 0.20 | | | [91] |
| | 3.82 | 21.21 | 69.04 | 9.75 | 44.29 | 5.63 | 49.76 | 0.32 | | | 13,445 | [44] |
| | 2.64 | 6.30 | 85.46 | 8.25 | | | | | | | | [95] |
| | 2.53 | 9.12 | 80.84 | 10.04 | 43.99 | 1.31 | 54.54 | 0.03 | 0.02 | 0.10 | 14,811 | [103] |
| | 2.13 | | | | 43.11 | 6.12 | 49.76 | 0.18 | 0.10 | 0.73 | | [15] |
| | 2.11 | 35.35 | 61.47 | 3.19 | | | | | | | | [51] |
| | 1.39 | | | | 38.29 | 6.10 | 54.50 | 0.25 | 0.86 | | 13,830 | [104] |
| | | | | | 47.78 | 6.27 | 45.15 | 0.80 | | | | [92] |
| | | | | | 48.73 | 7.09 | 43.59 | 0.44 | 0.15 | | | [100] |
| | | 2.28 | 77.35 | 20.37 | 43.36 | 6.46 | 49.51 | 0.37 | 0.30 | | | [52] |
| | | | | | 46.32 | 6.21 | 46.95 | 0.32 | 0.21 | | | [26] |
| | | | | | 48.40 | 6.30 | 44.90 | 0.20 | 0.10 | 0.10 | | [94] |
| | | | | | 44.50 | 5.97 | 49.22 | 0.16 | 0.15 | | | [105] |
| | | | | | | | | | | | 16,600 | [83] |
| | | 4.27 | 85.19 | 10.54 | | | | | | | | [106] |
| | | 11.95 | 71.85 | 16.20 | | | | | | | 14,874 | [47] |
| | | 12.70 | 84.36 | 2.94 | | | | | | | | [96] |
| | | | | | | | | | | | 16,437 | [107] |
| Textiles | 0.17 | 1.04 | 87.16 | 11.80 | 63.46 | 3.44 | 32.90 | 0.08 | 0.06 | 0.06 | 23,080 | [50] |
| | 1.10 | 1.57 | 89.57 | 8.87 | 58.74 | 5.44 | 35.53 | 0.13 | 0.15 | | 22,495 | [90] |
| | 3.92 | 0.87 | 83.33 | 15.80 | 58.02 | 4.77 | 35.11 | 1.93 | 0.17 | | 21,988 | [87] |
| | 2.37 | 0.42 | 86.84 | 12.74 | 61.55 | 2.86 | 34.98 | 0.37 | 0.24 | | 21,797 | [108] |
| | 10.00 | | | | 56.38 | 6.77 | 31.98 | 4.72 | 0.15 | | 21,083 | [97] |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1.37 | 0.34 | 88.34 | 11.33 | 56.56 | 5.15 | 36.16 | 2.13 | 0.00 | | 21,020 | [44] |
| | | 7.65 | 73.65 | 18.70 | | | | | | | 18,660 | [47] |
| | | 8.52 | 78.56 | 12.92 | 48.18 | 5.34 | 45.69 | 0.41 | 0.38 | | 18,123 | [109] |
| | | 8.60 | 78.45 | 12.95 | 48.12 | 5.47 | 45.67 | 0.32 | 0.42 | | 18,122 | [7] |
| | 45.40 | | | | | | | | | | 17,807 | [76] |
| | 5.53 | 0.75 | 86.70 | 12.54 | 49.91 | 6.00 | 43.68 | 0.26 | 0.15 | | 17,607 | [23] |
| | | 1.21 | 80.80 | 17.99 | 45.93 | 6.64 | 45.87 | 1.36 | 0.20 | | | [52] |
| | 5.78 | 3.74 | 78.42 | 17.84 | 55.69 | 7.76 | 33.34 | 2.81 | 0.40 | | | [81] |
| | 4.72 | 9.33 | 74.50 | 16.16 | | | | | | | | [46] |
| | 6.30 | 2.13 | 85.49 | 12.38 | | | | | | | | [42] |
| | 5.20 | 0.61 | 88.1 | 11.29 | 54.89 | 5.35 | 37.17 | 2.46 | 0.13 | | | [80] |
| | 52.70 | 6.28 | 79.32 | 14.40 | | | | | | | | [83] |
| | 60.33 | 3.86 | 83.79 | 12.35 | | | | | | | | [83] |
| | 25.00 | | | | 50.99 | 6.87 | 37.13 | 4.26 | 0.38 | 0.37 | | [85] |
| | 10.00 | | | | 49.59 | 6.61 | 41.32 | 2.27 | 0.21 | | | [110] |
| | 6.48 | | | | 56.14 | 6.47 | 33.51 | 3.45 | 0.43 | | | [78] |
| | 1.09 | | | | 55.87 | 5.05 | 36.86 | 1.23 | 0.10 | 0.89 | | [15] |
| | | | | | 45.30 | 6.50 | 47.60 | 0.30 | 0.20 | 0.10 | | [94] |
| | | | | | 57.06 | 6.85 | 35.54 | 0.43 | 0.12 | | | [105] |
| | | | | | 55.26 | 6.84 | 34.74 | 3.16 | 0.00 | | | [92] |
| | | | | | 54.05 | 6.60 | 36.94 | 1.99 | 0.41 | | | [100] |
| PE | 0.00 | 0.60 | 99.40 | 0.00 | 85.50 | 14.20 | 0.00 | 0.00 | 0.30 | 0.00 | | [111] |
| | 0.00 | 0.58 | 99.42 | 0.00 | 85.44 | 14.24 | 0.32 | 0.00 | 0.00 | 0.00 | | [112] |
| | | | | | 85.85 | 14.15 | 0.00 | 0.00 | 0.00 | 0.00 | | [113] |
| | 0.00 | 0.30 | 99.70 | 0.00 | 85.50 | 14.30 | 0.00 | 0.00 | 0.20 | 0.00 | | [111] |
| | 0.00 | 0.31 | 99.69 | 0.00 | 85.51 | 14.30 | 0.19 | 0.00 | 0.00 | 0.00 | | [112] |
| | | | | | 85.30 | 14.30 | 0.30 | 0.00 | 0.10 | | | [94] |
| | 0.17 | 0.00 | 99.98 | 0.02 | 85.98 | 11.20 | 2.44 | 0.21 | 0.17 | 0.00 | 46,480 | |
| | 0.00 | 0.00 | 100.00 | 0.00 | 86.03 | 13.12 | 0.87 | 0.00 | 0.00 | 0.00 | 35,725 | [109] |
| | 0.17 | 0.06 | 99.94 | 0.00 | 86.66 | 13.26 | 0.00 | 0.06 | 0.02 | 0.00 | 37,600 | [102] |
| | 0.02 | 0.15 | 99.85 | 0.00 | 85.94 | 13.88 | 0.00 | 0.12 | 0.06 | | 40,983 | [114] |
| | 0.25 | | | | 85.62 | 13.86 | 0.00 | 0.51 | 0.00 | 0.00 | 44,263 | [115] |
| | 0.02 | 0.15 | 99.85 | 0.00 | 85.45 | 14.32 | 0.00 | 0.16 | 0.07 | 0.00 | 46,318 | [87] |
| | 0.39 | 0.30 | 99.70 | 0.00 | 84.97 | 14.30 | 0.00 | 0.70 | 0.02 | 0.00 | 46,479 | [99] |
| | 0.20 | 1.20 | 98.70 | 0.10 | 85.20 | 14.20 | 0.00 | 0.10 | 0.10 | | 43,552 | [84] |
| | 0.28 | 1.42 | 98.58 | 0.00 | 85.15 | 14.36 | 0.22 | 0.07 | 0.19 | 0.00 | 47,285 | [116,117] |
| | 0.57 | 2.59 | 97.41 | 0.00 | | | | | | | | [95] |
| | 0.09 | 0.56 | 98.96 | 0.48 | 85.34 | 14.57 | 0.09 | 0.00 | 0.00 | | | [118] |
| | | | | | 85.59 | 14.41 | 0.00 | 0.00 | 0.00 | | | [119] |
| | | | | | 86.54 | 13.61 | 0.00 | 0.00 | 0.00 | 0.00 | | [120] |
| | | | | | 85.96 | 14.04 | 0.00 | 0.00 | 0.00 | 0.00 | | [121] |
| | | | | | 86.10 | 13.00 | 0.90 | 0.00 | 0.00 | | | [122] |
| PP | 0.05 | 0.02 | 99.98 | 0.00 | | | | | | | 45,200 | |
| | 0.00 | 0.16 | 99.84 | 0.00 | 84.30 | 14.44 | 1.05 | 0.18 | 0.03 | | 45,769 | [123] |
| | 0.05 | 0.02 | 99.97 | 0.01 | 85.41 | 12.51 | 1.85 | 0.23 | 0.00 | | 46,239 | [124] |
| | 0.00 | 0.82 | 99.18 | 0.00 | 83.75 | 13.98 | 2.27 | 0.00 | 0.00 | 0.00 | | [112] |
| | 0.00 | 1.10 | 98.90 | 0.00 | | | | | | | | [111] |
| | 0.23 | 0.08 | 99.79 | 0.13 | 84.62 | 15.23 | 0.00 | 0.14 | 0.01 | 0.00 | | [125] |
| | | | | | 85.22 | 13.70 | 1.08 | 0.00 | 0.00 | 0.00 | | [126] |
| | | | | | 85.10 | 14.40 | 0.50 | 0.00 | 0.00 | | | [94] |
| | | | | | 86.72 | 13.28 | 0.00 | 0.00 | 0.00 | | | [119] |
| | | | | | 86.39 | 13.61 | 0.00 | 0.00 | 0.00 | 0.00 | | [120] |
| PS | 0.45 | 0.04 | 99.57 | 0.39 | | | | | | | 38,930 | |
| | 0.20 | 0.50 | 99.40 | 0.10 | 87.10 | 8.40 | 4.00 | 0.20 | 0.00 | | | [84] |
| | 0.00 | 0.51 | 99.49 | 0.00 | 91.08 | 7.68 | 1.24 | 0.00 | 0.00 | 0.00 | | [112] |
| | 0.06 | 0.01 | 99.39 | 0.60 | | | | | | | | [103] |
| | | | | | 89.20 | 9.00 | 1.80 | 0.00 | 0.00 | | | [94] |
| | | | | | 89.06 | 10.02 | 0.55 | 0.00 | 0.37 | | | [119] |
| | | | | | 92.14 | 7.86 | 0.00 | 0.00 | 0.00 | 0.00 | | [120] |
| | | | | | 87.76 | 9.25 | 5.30 | 0.00 | 0.04 | 0.00 | | [127] |
| PVC | 0.78 | 8.74 | 79.81 | 11.45 | 37.81 | 4.25 | 0.00 | 0.09 | 0.19 | 57.66 | | [128] |
| | 0.30 | 14.36 | 65.17 | 20.47 | 38.82 | 5.10 | 0.00 | 0.06 | 0.30 | 55.72 | | [129] |
| | 0.28 | 14.99 | 65.06 | 19.95 | 40.39 | 4.54 | 0.21 | 0.20 | 0.09 | 54.56 | 15,876 | [102] |
| | 0.26 | 0.32 | 91.25 | 8.43 | 41.79 | 4.84 | 0.00 | 0.09 | 0.02 | 53.26 | 21,732 | [130] |
| | 0.24 | 0.00 | 93.71 | 6.29 | | | | | | | | [104] |
| | 0.23 | 0.20 | 91.99 | 7.81 | 52.30 | 5.11 | 0.00 | 0.15 | 0.06 | 42.37 | 22,646 | [108] |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.23 | 0.00 | 95.46 | 4.54 | | | | | | | | [45] |
| | 0.20 | 2.10 | 87.07 | 10.82 | 46.12 | 5.71 | 1.63 | 0.10 | 0.10 | 46.33 | 22,735 | [84] |
| | 0.20 | 0.04 | 95.16 | 4.80 | 38.75 | 5.21 | 0.00 | 0.22 | 0.00 | 55.82 | 22,566 | [44] |
| | 0.16 | 0.00 | 94.93 | 5.07 | 38.34 | 4.47 | 0.00 | 0.23 | 0.61 | 56.35 | 20,830 | |
| | 0.12 | 0.08 | 93.96 | 5.96 | 40.38 | 5.83 | 0.00 | 0.07 | 1.25 | 52.46 | 22,405 | [131] |
| | 0.11 | | | | 40.78 | 5.73 | 0.00 | 0.02 | 0.09 | 53.38 | 20,079 | [127] |
| | 0.02 | 0.10 | 94.50 | 5.40 | 38.83 | 4.57 | 0.00 | 0.01 | 0.00 | 56.60 | 21,682 | [103] |
| | 0.00 | 14.12 | 71.39 | 14.49 | 40.91 | 4.80 | 0.00 | 0.06 | 0.01 | 54.23 | | [116] |
| | 0.00 | 3.50 | 83.73 | 12.77 | | | | | | | | [96] |
| | | | | | 40.80 | 5.20 | 5.30 | 0.00 | 0.00 | 48.70 | | [94] |
| | | | | | 38.40 | 4.80 | 0.00 | 0.00 | 0.00 | 56.80 | | [132] |
| | | | | | 38.15 | 5.18 | 2.30 | 0.00 | 0.21 | 54.16 | | [133] |
| | | | | | 36.83 | 4.71 | 0.00 | 0.05 | 0.25 | 58.15 | | [113] |
| Rubber | 1.90 | 43.62 | 54.10 | 2.27 | | | | | | | | [49] |
| | 0.22 | 41.43 | 42.75 | 15.81 | | | | | | | | [87] |
| | 0.62 | 39.92 | 47.12 | 12.96 | 80.05 | 7.99 | 6.00 | 1.79 | 4.17 | | 21,812 | [99] |
| | 0.54 | 29.10 | 52.63 | 18.27 | | | | | | | | [48] |
| | 0.63 | 26.48 | 56.37 | 17.16 | 74.90 | 7.17 | 14.52 | 1.55 | 1.86 | | 23,291 | [108] |
| | 0.78 | 25.7 | 68.05 | 6.25 | 79.19 | 8.45 | 11.38 | 0.69 | 0.28 | | 26,491 | [134] |
| | 0.32 | 23.66 | 69.88 | 6.46 | | | | | | | 22,669 | [108] |
| | 0.99 | 19.27 | 63.11 | 17.61 | 88.56 | 8.52 | 0.88 | 0.75 | 1.29 | | 30,164 | [135] |
| | 1.94 | 16.02 | 59.92 | 24.06 | 84.21 | 7.73 | 5.29 | 0.61 | 2.16 | | | [129] |
| | 0.65 | 15.38 | 65.26 | 19.36 | 89.18 | 8.54 | 0.00 | 1.23 | 1.05 | | 33,402 | [104] |
| | 1.14 | 14.56 | 80.70 | 4.74 | 86.13 | 6.94 | 3.47 | 0.58 | 1.73 | 1.16 | | [136] |
| | 0.65 | 13.98 | 67.20 | 18.83 | 88.82 | 8.83 | 0.00 | 1.27 | 1.08 | | | [80] |
| | 0.00 | 13.50 | 58.80 | 27.70 | 85.75 | 11.49 | 0.55 | 0.55 | 1.66 | | | [91] |
| | 0.93 | 10.24 | 62.83 | 26.93 | 89.53 | 6.70 | 1.07 | 0.69 | 2.02 | | 35,740 | |
| | 1.10 | 9.91 | 86.15 | 3.94 | | | | | | | 25,693 | [42] |
| | 0.00 | 8.98 | 64.72 | 26.30 | | | | | | | | [137] |
| | 1.23 | 8.36 | 84.77 | 6.86 | 77.72 | 10.12 | 7.42 | 0.00 | 2.66 | 2.08 | 25,177 | [43] |
| | 0.80 | 7.47 | 65.16 | 27.37 | 86.03 | 7.23 | 4.56 | 0.40 | 1.78 | | | [138] |
| | 0.55 | 7.11 | 63.00 | 29.89 | 81.66 | 7.23 | 9.54 | 0.65 | 0.92 | | | [139] |
| | 0.99 | 6.14 | 66.12 | 27.73 | 85.98 | 11.50 | 0.79 | 0.64 | 1.10 | | | [81] |
| | 1.09 | 5.00 | 74.55 | 20.44 | 86.70 | 7.28 | 2.14 | 2.42 | 1.47 | | 37,299 | [140] |
| | 1.80 | 4.89 | 68.13 | 26.99 | 82.65 | 7.55 | 7.45 | 1.67 | 0.67 | | | [141] |
| | 1.14 | 4.39 | 62.96 | 32.65 | 89.24 | 7.12 | 1.52 | 0.41 | 1.70 | | | [142] |
| | 0.75 | 4.19 | 65.44 | 30.37 | 83.92 | 6.83 | 7.55 | 0.78 | 0.92 | | 38,868 | [143] |
| | 0.21 | 3.90 | 63.13 | 32.97 | 88.84 | 7.74 | 0.94 | 0.32 | 2.16 | | 37,929 | [144] |
| | 0.80 | 3.33 | 69.25 | 27.42 | 85.63 | 7.86 | 4.65 | 0.52 | 1.34 | | 36,757 | [145] |
| | | | | | 81.50 | 8.79 | 7.09 | 0.62 | 2.01 | | | [146] |
| | | | | | 78.48 | 13.26 | 6.55 | 0.36 | 1.35 | | | [105] |
| | 2.00 | | | | 86.67 | 11.11 | 0.00 | 2.22 | 0.00 | | 25,901 | [97] |
| | 1.20 | | | | 87.13 | 10.88 | 0.00 | 0.00 | 2.00 | | 25,638 | [84] |

Remark: the data without reference were from our own research.

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